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CRYOGENIC AND SUPERCONDUCTING MAGNET RESEARCH AT THE NASA LEWIS RESEARCH CENTER

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ABSTRACT

A research and development program is underway at the Lewis Research Center to produce strong magnetic fields in large test volumes with minimum weight and power consumption. A high-field liquid-neon-cooled aluminum magnet and various superconducting magnets and their uses are discussed.

SUMMARY

Cryogenically cooled and superconducting electromagnets of large volume for research in plasma and solid state physics have been designed, constructed, and tested at the NASA Lewis Research Center. One system of coils, wound from ultrapure (99.9983 percent pure) aluminum and cooled with liquid neon, has produced steady-state fields as large as 20.0 T in an 11.2 cm bore and 14.0 T in a 30 cm bore. Both magnets are in current use, providing intense fields with large test volume. Superconducting coils have been wound from niobium-zirconium, niobium-titanium, and niobium-tin conductors. These have produced fields as intense as 15.0 tesla with niobium-tin coils having a 15-cm bore.

INTRODUCTION

Research on advanced propulsion and power concepts at the NASA Lewis Research Center requires magnetic fields of large volume and high field

strength. To satisfy these needs a program of design, development, and testing of magnets has been under way for several years. The program has been concerned with three types of electromagnets: (1) copper coils cooled with water, (2) aluminum coils cryogenically cooled, and (3) superconducting coils.

These electromagnets have been and are being used for investigations in plasma and solid-state physics, biomagnetic effects, and in other fields. The cryogenically cooled and superconducting magnets and some of their uses will be described.

CRYOGENICALLY COOLED COILS

The cryogenically cooled aluminum electromagnets (Ref. 1) were designed at Lewis Research Center and were produced under contracts for the component parts. Assembly and testing were done at Lewis.

High purity aluminum was selected as the conductor because of the magnetoresistance characteristics of aluminum. The resistance of aluminum changes in a magnetic field, increasing at low fields and saturating at high fields. This saturation in magnetoresistance is a function of both the temperature and the purity of the conductor. The highest purity available in large quantities at a reasonable price was 0.999983 and this was the conductor selected for the coils. Extensive measurements of the magnetoresistance of 0.99999+ and 0.999983 pure aluminum were made at the National Bureau of Standards and at the Lewis Research Center. These results are shown in Fig. 1. Similar measurements of the magnetoresistance of copper did not show this saturation. Hence, aluminum was the choice.

The selection of a coolant was likewise dictated by practical considerations. Liquid helium was not used because of its low latent heat of vapor-

ization. Liquid hydrogen was not considered for use as a primary cooling medium because of the explosion hazard.

A gaseous helium system was considered, but was found to be not economically competitive. Liquid neon was chosen as the best available coolant because it is inert and is available in reasonable quantities as a byproduct of the steel industry's liquid oxygen plants.

The liquid neon plant used in this installation, shown schematically in Fig. 2, has been previously described (Ref. 2). A study of the boiling neon heat transfer characteristics was made at Lehigh University (Ref. 3).

The neon liquefication system consists of high-pressure gaseous neon storage and pumping facilities, liquid hydrogen or refrigerated gaseous-helium heat exchanger for condensing the neon, liquid-neon storage, the magnet vessels, and low-temperature gaseous-neon storage. During magnet operation the neon boils off and collects in the gaseous-neon storage vessel. Reliquefication of the approximately 1600 liters neon charge requires about 18 hours, including startup after a 40-hour shutdown.

The magnet facility consists of two magnets, one having a bore diameter of 11 cm ($4\frac{1}{2}$ in.), the other 30 cm (12 in.), each with its own containment vessel. A cutaway drawing of the 30-cm-bore magnet assembly and its vessel is shown in Fig. 3. The magnet consists of a stack of up to 12 coils, each of approximately 5.7 cm thickness, separated by radial spacer bars of epoxy and glass-fiber material. Outside winding diameter of the coils is 94 cm and the overall length is 76 cm.

Because the high-purity annealed aluminum is so soft, special methods had to be developed for handling the material and restraining the magnetic forces in the conductor. These details are shown in Fig. 4. A backup

channel of stainless steel contains the high purity aluminum which is bonded to it by a thermosetting adhesive. The flow channels for the coolant are formed by stainless steel spacers which are held in position by means of a thin (0.008 cm), stainless, corrugated carrier ribbon. Between turns, insulation is provided by a fiberglass scrim cloth. The complete package is wound up to form flat pancake coils. In all cases, pairs of coils are connected in series by welding at the hub sections. Pairs of coils then are joined by external conductors in series or parallel connections to match the current-voltage capabilities of the power supply. A photograph of a complete set of 12 coils (three paralleled sets of 4 coils in series) is shown in Fig. 5.

In operation the vacuum- and liquid-nitrogen-jacketed magnet vessel is charged with liquid neon to a depth of approximately 30 cm over the top of the coils. Pool boiling of the liquid neon within the coolant passages of each coil (aided by convective currents due to vigorous boiling) provides the required cooling. A homopolar generator (Ref. 4) supplies the current in a constant-voltage mode of control. The room-temperature resistance is approximately 37 mΩ per coil, and the liquid-neon-temperature (28° K) resistance is about 0.1 mΩ in zero magnetic field, which is a resistance ratio of about 400. In a test of eight 11 cm bore coils at 20.0 T the average resistance of one coil was about 0.5 mΩ as compared to 0.1 mΩ in zero field. The increase in resistance at a high-field condition is due to three separate effects: the magnetoresistance, the rise of conductor temperature necessary to transfer the heat produced, and the gradual rise of the temperature of the liquid-neon which is boiling under saturated conditions into the vapor tank. The variation of coil resistance as a function of current and neon-vapor

pressure is shown in Fig. 6. Also indicated are the temperatures corresponding to the vapor pressures. It is seen that a one-third change in resistance occurs for only 3° K increase in neon temperature. Gradual adjustment of generator voltage is thus required to maintain constant current. Unfortunately, it is impossible to take advantage of this strong temperature dependence by lowering the pressure on the neon to decrease its temperature, because the freezing point of saturated neon is only about 2° K below the boiling temperature at 1 atmosphere.

At the highest field strengths, the power consumption is 1 megawatt. The cooling capability of the liquid neon charge is approximately 1 megawatt-minute. With the fastest powering up and down schedules possible with the equipment available, a considerable fraction of the total neon charge must be allocated for these periods, and thus the time at full field is less than 1 minute/day. Maximum coil current is 15,200 amperes, the maximum field is 20 T for the 11.2 cm bore coil set and 15 T for the 30 cm bore coil set. Stored energy maxima are approximately 10 megajoules. These magnets are used principally for solid state physics and superconducting materials research.

The neon system capacity is 100,000 s.c.f. Loss rate of the neon gas from the system has been approximately 5 percent per year, with some additional losses being incurred when it was necessary to open the magnet vessel.

Availability of cryogenic liquids has been the key factor in the operation of these magnets and most of the research that is performed in them. Liquid nitrogen is used for precooling the magnets, as a radiation shield for the liquid neon and as current bus coolant. Liquid hydrogen (shown in Fig. 2) may be used to condense the neon. Liquid helium is used in most of the

experiments. The homopolar generator power supply uses, in place of brushes, a liquid metal alloy of sodium and potassium which requires an inert, dry cover gas atmosphere. High purity argon obtained from evaporation of the liquid has proven to be a most reliable source for this cover gas.

SUPERCONDUCTING MAGNETS

The phenomenon of superconductivity in metals was first observed in the early 1900's. It is characterized by a total loss of resistance to electrical current in a step transition as temperature is reduced to near absolute zero. Since the first studies of the phenomenon, nearly all metals have been categorized as either superconducting or ferromagnetic at very low temperatures. Most of the metals revert to their normal resistance characteristics in relatively low magnetic field environments. It was not until 1961 with the discovery of materials capable of retaining their superconducting characteristics at high field strengths (over 20 T), relatively high temperatures (to 20^{o} K), and while carrying high current densities (over 10^{6} A/cm^{2}), that significant commercial use of superconductors could be made. The values cited are not mutually independent, but are rather the extreme values of a bounding surface between the superconducting and normal states as indicated on Fig. 7.

Even today, with rather widespread use of superconducting devices, the potential capabilities offered by the materials cannot be fully achieved in hardware. When wound into coils the superconductors were found to behave quite differently than when tested in short sample lengths. This was due primarily to penetrations of magnetic flux into the material in discrete bundles called "flux jumps." Propagating normal resistance regions can

and do result from such flux penetrations. Addition of sufficient copper paralleling the superconductor to shunt, at least temporarily, the current around the normal region has allowed the use of superconductors up to their critical current values, but at a considerable reduction in current density. These composite conductors are known as "stabilized conductors" and were first demonstrated in 1965 (Ref. 5). Efforts to obtain the benefits of stabilization with reduced penalties are continuing.

The Lewis Research Center has acquired a number of superconducting magnets with a large range of size and field strength. Table I shows some of these magnets and their pertinent dimensions and uses. The cryostats for these various magnets vary in size from a few liters to over 1400 liters liquid helium capacity. Boil-off gas from the larger facilities is collected, and reliquefied in a system consisting of two hemispherical balloons 27.5 meters in diameter, a purification system and two 100 liter per hour liquefiers. This liquid helium system was originally acquired for, and is mostly used by, a space environment simulation facility. A photograph of the upper section of the largest magnet cryostat is shown in Fig. 8. It has an i.d. of 96.5 cm, and is 4.3 meters tall.

Some of the smaller magnets are similar to those used at various other laboratories so the remaining discussion will be concerned with those that are unique to Lewis.

The highest field attained thus far with superconducting magnets anywhere is about 15.0 tesla, which was attained with the 15 cm (6 in.) bore magnet[1] at Lewis. This magnet has a test volume approximately 9 times that of the other highest field superconducting magnets.

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[1]Contract No. NAS3-7101 RCA.

Design and construction of the magnet (Ref. 6) presented some problems which, though not unique, were intensified by the size and field strength requirements. The magnet is a solenoid having approximate dimensions of 15-cm i.d., 50-cm o.d., and a length of 35 cm. Weight of the magnet is nearly 450 kg (1000 lb) and the stored energy when powered to maximum field strength approaches 2 MJ. A photograph of the magnet is shown in Fig. 9.

MAGNET DESIGN AND CONSTRUCTION

At present, the only superconducting material which is suitable for use in a magnetic environment greater than about 10 T is Nb_3Sn. The 90,000 m of 0.23-cm-wide superconductive ribbon used in the 15-cm-bore magnet is a composite of Nb_3Sn, stainless steel, and silver. Stainless steel serves as a substrate for the vapor-deposited Nb_3Sn and provides the high strength required. Silver plating is added to improve the stability of the superconductor. The thickness of each material varies depending upon the characteristics desired. Over-design in strength, stability, or unused current-carrying capacity is costly in terms of current density and as a result is costly in magnet volume, materials, and performance.

Selection of the conductor to match the field, strength, and stability requirements in different sections of the magnet led immediately to a modular design concept. Hoop stress on the conductor and compressive loading of the magnet windings and internal structure are necessarily high because of the high current densities required. Axial compressive loading of the windings builds up throughout the magnet due to the attractive force between conductors. To prevent compressive stress from exceeding the strength limits of the materials, load-bearing radial and axial members (the module walls)

were necessary to accept and transmit forces at various points in the magnet. An iterative computer program was used to optimize the design, both from strength and conductor characteristics considerations. This work has been reported previously (Ref. 7). Figure 10 shows the various parts of the magnet. Twenty-two coil forms were used to wind the thirty electrically distinct modules.

Because of the large mass of the magnet, cooling of the internal parts was essential. Passages in the form of grooves and holes in the support structure provided for the inflow of liquid helium and for the escape of helium gas generated by localized "flux jump" penetrations or general transitions from superconductive to resistive modes. These transitions result in the collapse of the field and the release of all of the stored energy in a very short time period, so that the magnet is heated and the helium is vaporized.

MAGNET SYSTEM

The complete magnet system with the exception of liquid helium and nitrogen supply and helium gas recovery systems is shown in Fig. 11. The control cabinet has provisions for remote control of the 100-A, 8-V power supplies, synchronized ramping of the current to each magnet section, meter read-out of all instrumentation and liquid helium level indication.

The Dewar is 71-cm i.d., 2.4-m tall and has liquid nitrogen shielded walls and a liquid nitrogen cooled lid with copper radiation shields. Power leads pass through and are thermally connected to the lid nitrogen chamber. An insert Dewar (not shown) allows room temperature or pumped helium environment in the magnet bore.

LIQUID HELIUM CONSUMPTION

Capacity of the Dewar is approximately 200 liters of liquid helium. Boil-

off rate of the Dewar alone is approximately 1 liter/hr. With the magnet installed and power and instrument leads connected, the boil-off is 3 liters/hr. Power dissipation during magnet charging boils off 25 to 60 liters/hr. During a 62-hr, 10-T test, 8 W of power were required continuously, corresponding to about 11 liters/hr.

Four[2] of the six 51-cm magnets (shown in Fig. 12) are quite similar in construction and materials to the 15-cm magnet. These magnets are not made from "Stabilized material" although one of the 51-cm magnets does use a copper clad conductor. As a result all of these magnets are readily triggered into the superconducting to normal transition or "quench," and none achieved design goals of current carrying capacity or field strength in their initial tests. However, by operating the magnets in "superfluid" helium, design values were for the most part obtained. Magnet performance was improved by factors from 1.3 to 1.6 over the performance obtained using 4.2° K helium.

Superfluid helium occurs as an increasing portion of liquid helium as the temperature is reduced below 2.17° K. The characteristics of the superfluid are no less amazing than those of a superconductor, and indeed there are theoretical analogies between the two. The superfluid is obtained by reducing the pressure above the liquid to below 38 mm of mercury. At this pressure, called the λ point, a violent boiling suddenly takes place and almost immediately subsides. No bubble formation is observed at all as the pressure is further reduced, all vaporization of the liquid occurring at the surface. The two characteristics of the superfluid which make it

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[2]Contract No. NAS3-7928 RCA.

unique as a coolant are its extremely high thermal conductivity and extremely low viscosity. Within certain limits of heat flux all of the heat generated anywhere in the liquid is conducted essentially instantaneously to the surface of the liquid. Combine this behavior with, for all practical purposes, zero viscosity and one has a coolant that literally searches for heat, penetrating even the smallest opening. The result, for magnet operation, is improved stability and an ability to power the magnet to near the critical current value for a short sample of the material at a field strength corresponding to the highest value prevailing in the magnet.

The remaining two 51-cm bore magnets[3] not previously discussed are wound of stabilized NbTi and Nb_3Sn. These magnets are each 80 cm o. d. and 30 cm long. The magnets are made in three concentric modules and use relatively large conductors, utilizing higher currents and having much lower inductance than the previously discussed magnets. Design goals of 5.0 T for a single magnet and 8.8 T for a pair of magnets back-to-back with no separation have been achieved.

The innermost module consists of 20 submodules of 1.25-cm wide Nb_3Sn ribbon stabilized with copper and strengthened with stainless steel wound in pancake form. Outer modules are wound of 0.218-cm square composite copper and NbTi. Because this set of magnets is wound of stabilized materials little additional performance benefit can be realized by operation of these magnets in superfluid helium.

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[3]Contract No. NAS3-9684 AVCO.

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5. Kantrowitz, A. R., and Z. J. J. Stekly, Appl. Phys. Letters, 6, 56 (1965).

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TABLE I. - SUPERCONDUCTING MAGNETS

i. d., cm	No.	B_o, T	S. C.	Stabilization	Uses
5	1	5.0	NbZr	None	Solid state physics, Bio-Mag. Res.
7.5	1	10.0	Nb_3Sn	Partial	Solid state, thermo-power, fld emission
10	2	3.0	NbZr	None	Transverse fld, solid state physics
10	2	2.5	NbZr	None	Plasma physics
15	1	15.0	Nb_3Sn	None	Solid state physics, Bio-Mag. Res.
19	2	2.5	NbZr	None	Plasma physics
51	4	3.6 one 5.8 pr	Nb_3Sn	3 None, 1 partial	Plasma physics
51	2	5.0 one 8.8 pr	NbTi & Nb_3Sn	Total	Plasma physics

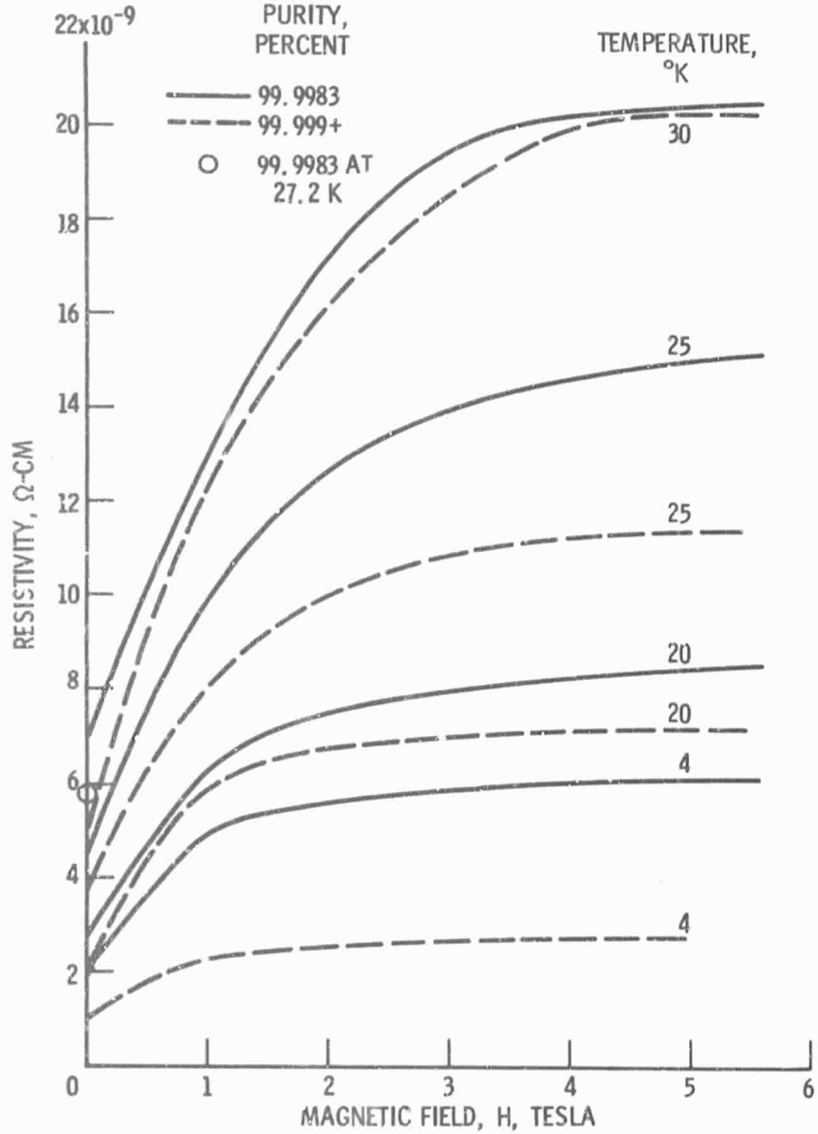

Figure 1. - Magnetoresistance of aluminum.

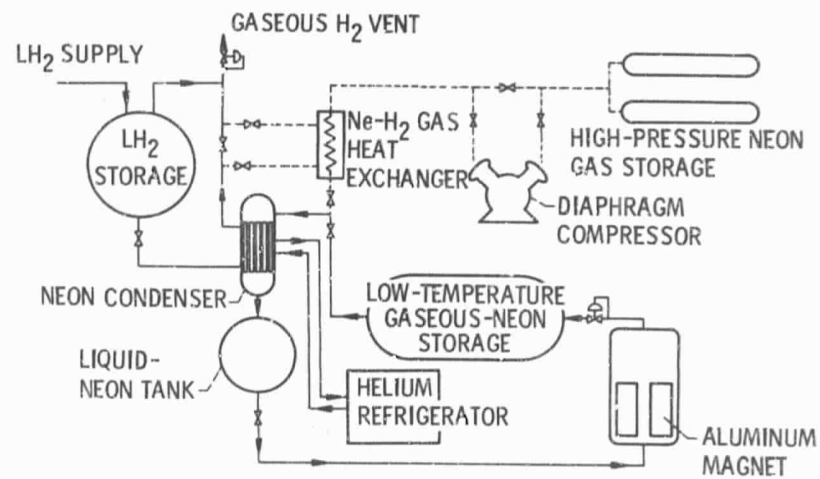

Figure 2. - Flow diagram of neon liquification system.

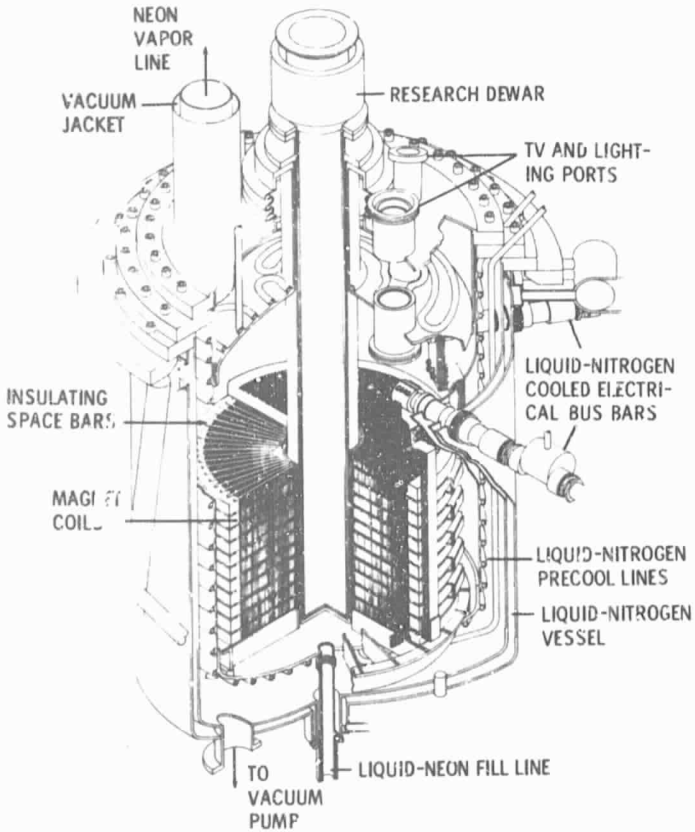

Figure 3. - 30-cm Coils in magnet vessel.

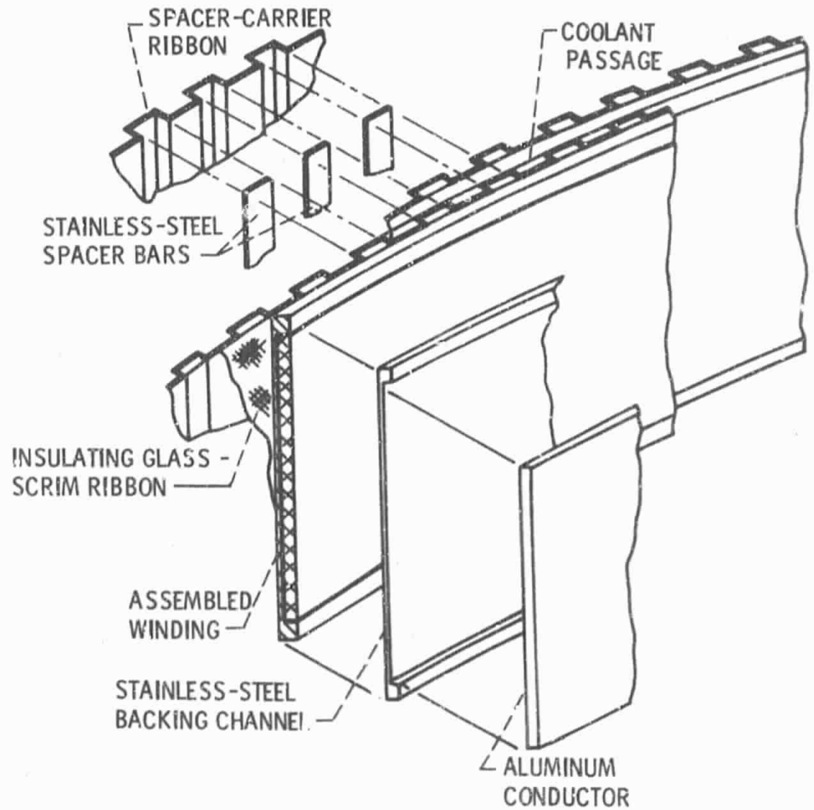

Figure 4. - Details of coil construction.

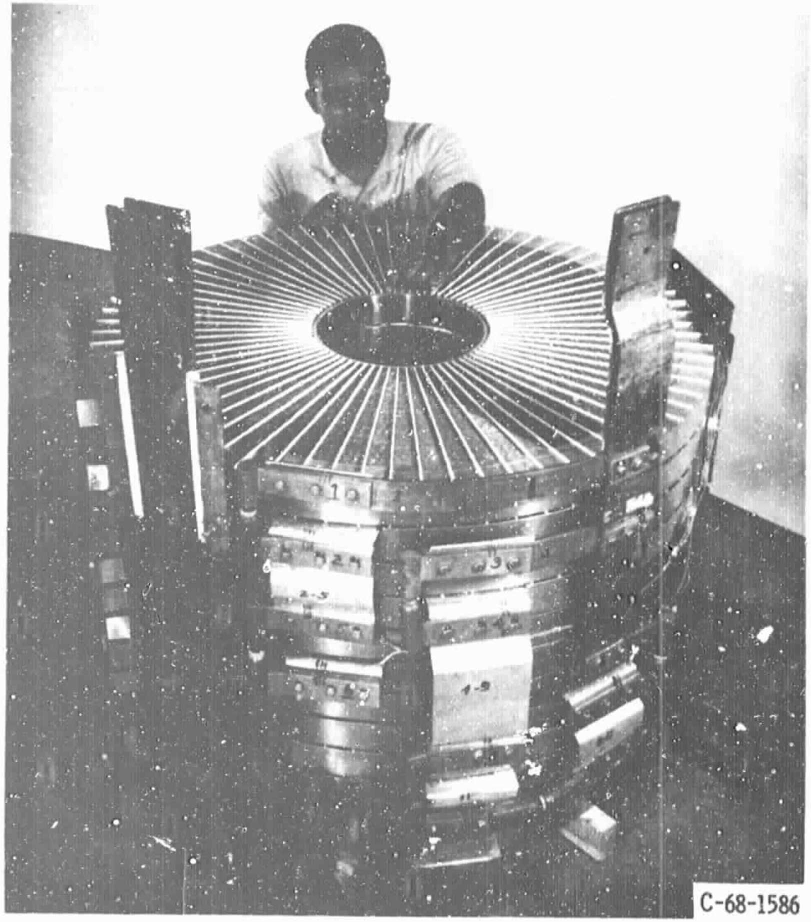

Figure 5. - Twelve 30-cm bore liquid neon cooled aluminum magnet coils.

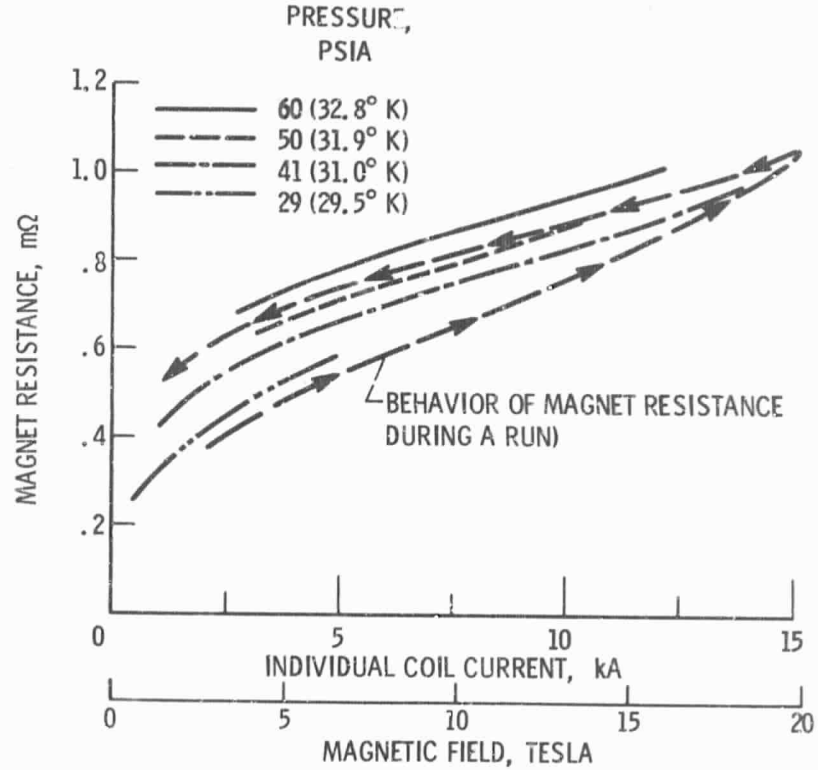

Figure 6. - Resistance of eight 11.3-cm. -bore coils (in series-parallel hookup) as function of individual coil current.

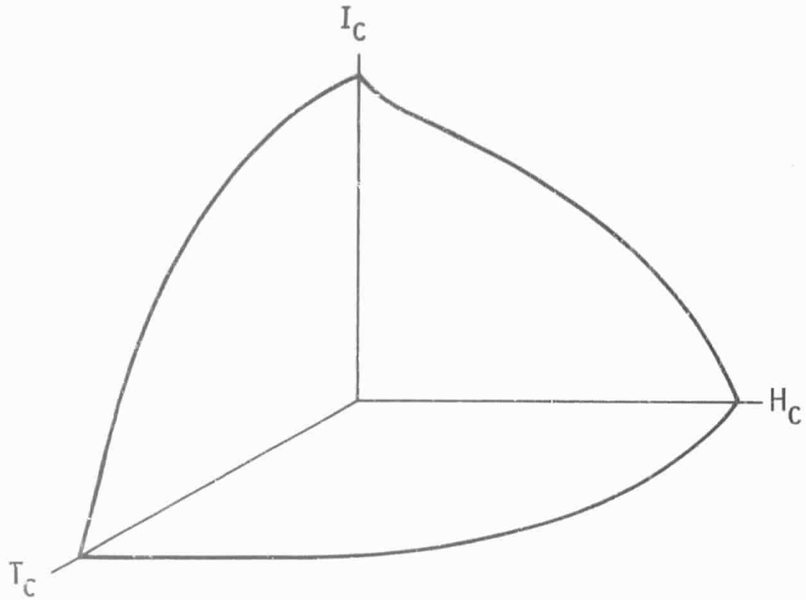

Figure 7. - Superconducting critical surface. Current, field and temperature boundaries.

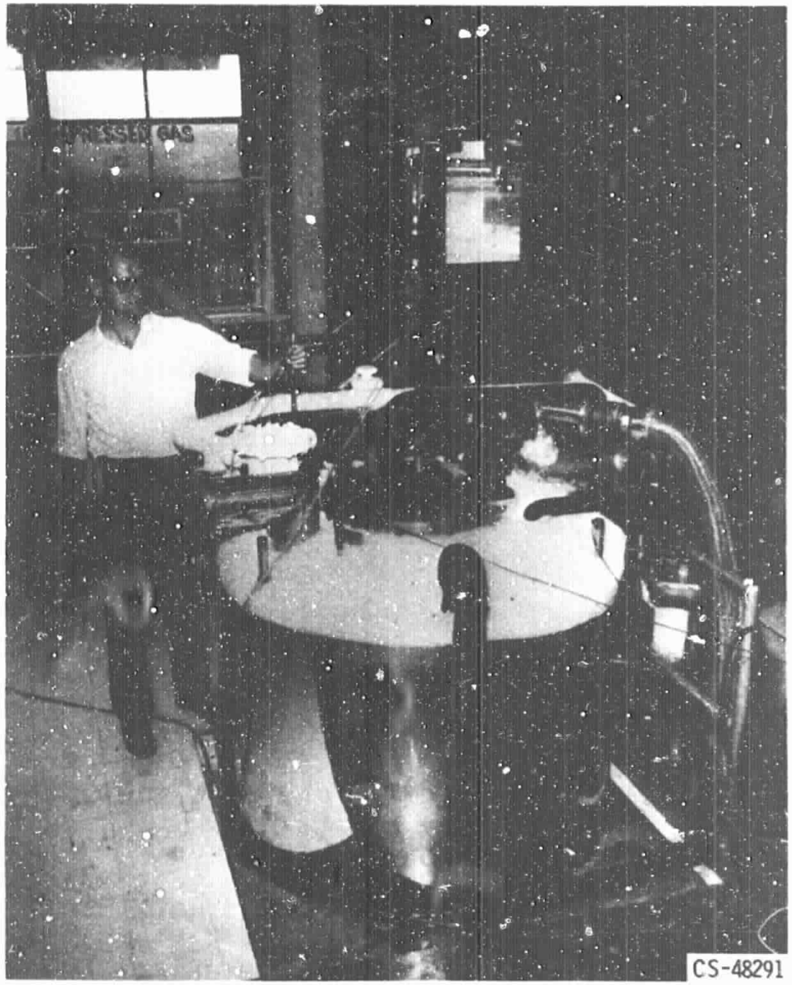

Figure 8. - Upper section of 96.5-cm I.D., 4.5-m tall dewar.

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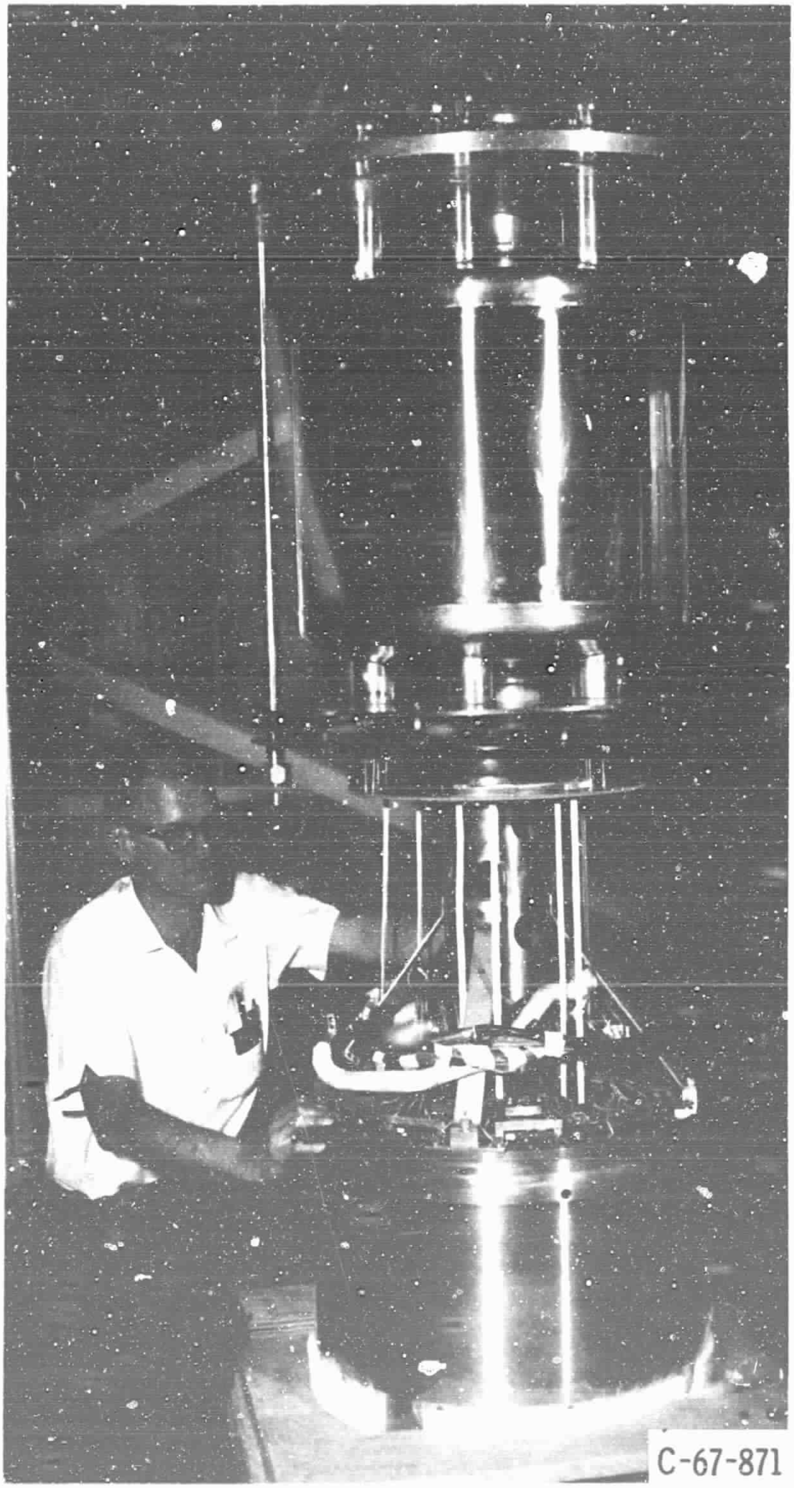

Figure 9. - 15-cm-bore, 14-T magnet and dewar lid.

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Figure 10. - Components of magnet.

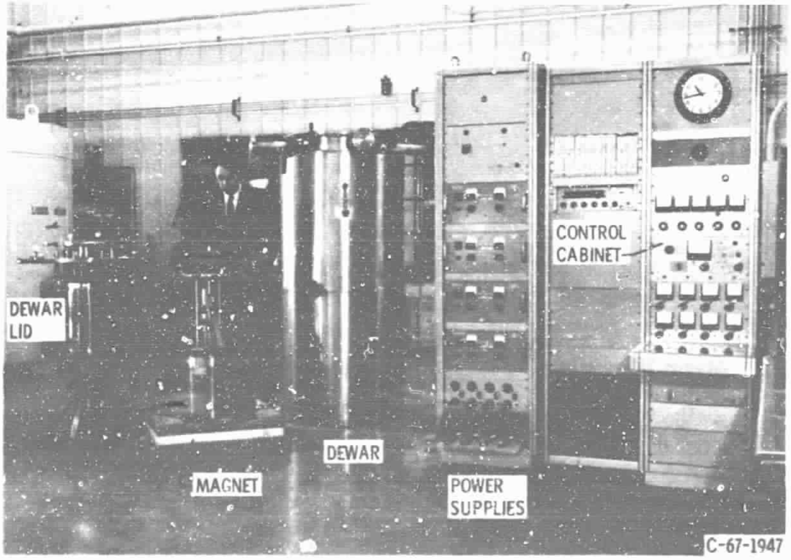

Figure 11. - Magnet system.

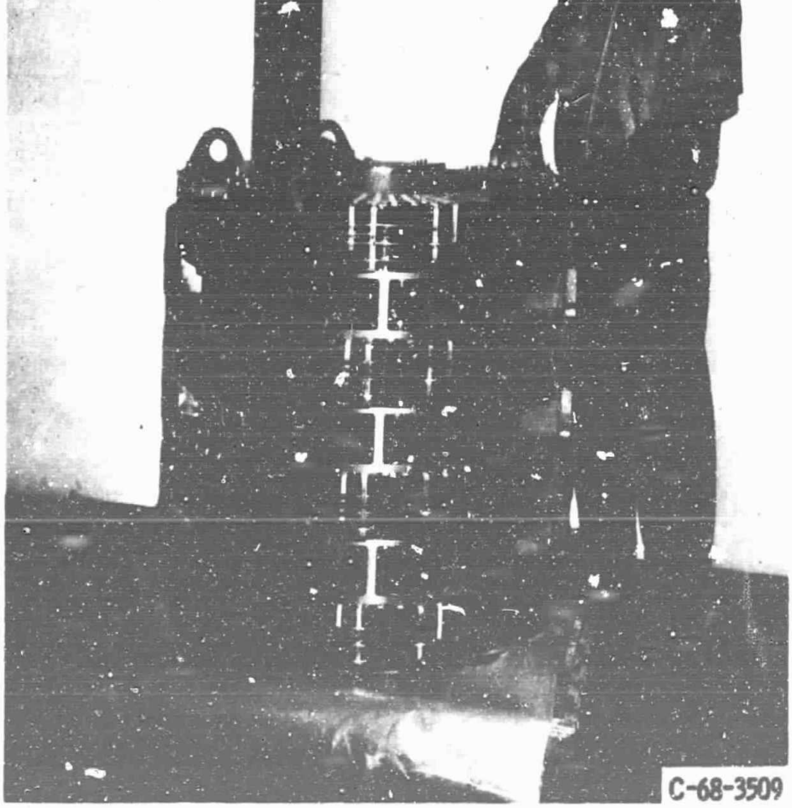

Figure 12. - Four 51-cm bore superconducting magnets.